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IITRI-B6020-5
(Bimonthly Report)

FIBER-REINFORCED METALS AND ALLOYS

Chief, Bureau of Naval Weapons
Department of the Navy
Washington 25, D. C.

Contract No. NOw-64-0066-c

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IIT RESEARCH INST[redacted]

Chicago, Ill[redacted]

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FIBER-REINFORCED METALS AND ALLOYS ,

~~IITRI-B6020~~-5

(~~Bimonthly Rep~~ort)

~~July 8, 1964 to September 8,~~ 1964

9 Bimonthly progress rept. no. 5, 8 Jul-8 Sep 64,

for

Chief, Bureau of Naval Weapons
Department of the Navy
Washington 25, D. C.

Attention: Code RRMA-222

October 26, 1964

FIBER-REINFORCED METALS AND ALLOYS

I. INTRODUCTION

This is the fifth bimonthly progress report on IITRI Project B6020 entitled, "Fiber-Reinforced Metals and Alloys," and covers the work done between July 8 and September 8, 1964.

The basic objective of the program is to investigate the fundamental factors affecting the fiber reinforcement of metals and alloys. The ultimate objective is to develop new materials possessing high strength-to-weight ratios. The majority of the current effort is devoted to the study of fundamental factors influencing the fiber reinforcement of metals. This report describes the work done on the mechanisms of strengthening and deformation, and the fracture behavior of composites of tungsten-silver and steel-silver with both short aligned fibers as well as long continuous fibers.

II. EXPERIMENTAL TECHNIQUES

The steel-silver composites prepared to date were fabricated by hot extrusion below the recrystallization temperature of steel. The composites made of tungsten-silver were prepared by infiltration of aligned tungsten wire bundles with silver below 1800°F. The composites prepared with short, discontinuous fibers were subsequently hot worked in order to reduce the interfiber spacings or effectively increase the volume fraction of fibers in the composites.

All studies on deformation and fracture behavior were made on samples that were metallographically polished prior to straining on the Instron tester. The microstrain work was performed with the use of the strain gages; actual strain was measured down to 2 or 3 x 10^{-6}. Interfiber spacings were measured with a Hurlbut counter.

The fracture energy measurements were made by the standard precracked plate technique. Using this technique, a precise notch of known radius of curvature is machined by the use of ultrasonic devices.

The sample is then pulled and the fracture stress measured. The fracture energy is then calculated from the Griffith-Orowan formula:

$$\sigma_F \approx \sqrt{\frac{2E\gamma}{\pi c}}$$

The fracture energy measurements were performed for all samples containing up to 70 v/o fibers. Because of the uncertainty of measurement of the value of c, the results are somewhat questionable with regard to the absolute numbers. However, it was noticed that the variation of fracture energy for any given composition was much less than one order of magnitude.

III. RESULTS AND DISCUSSION

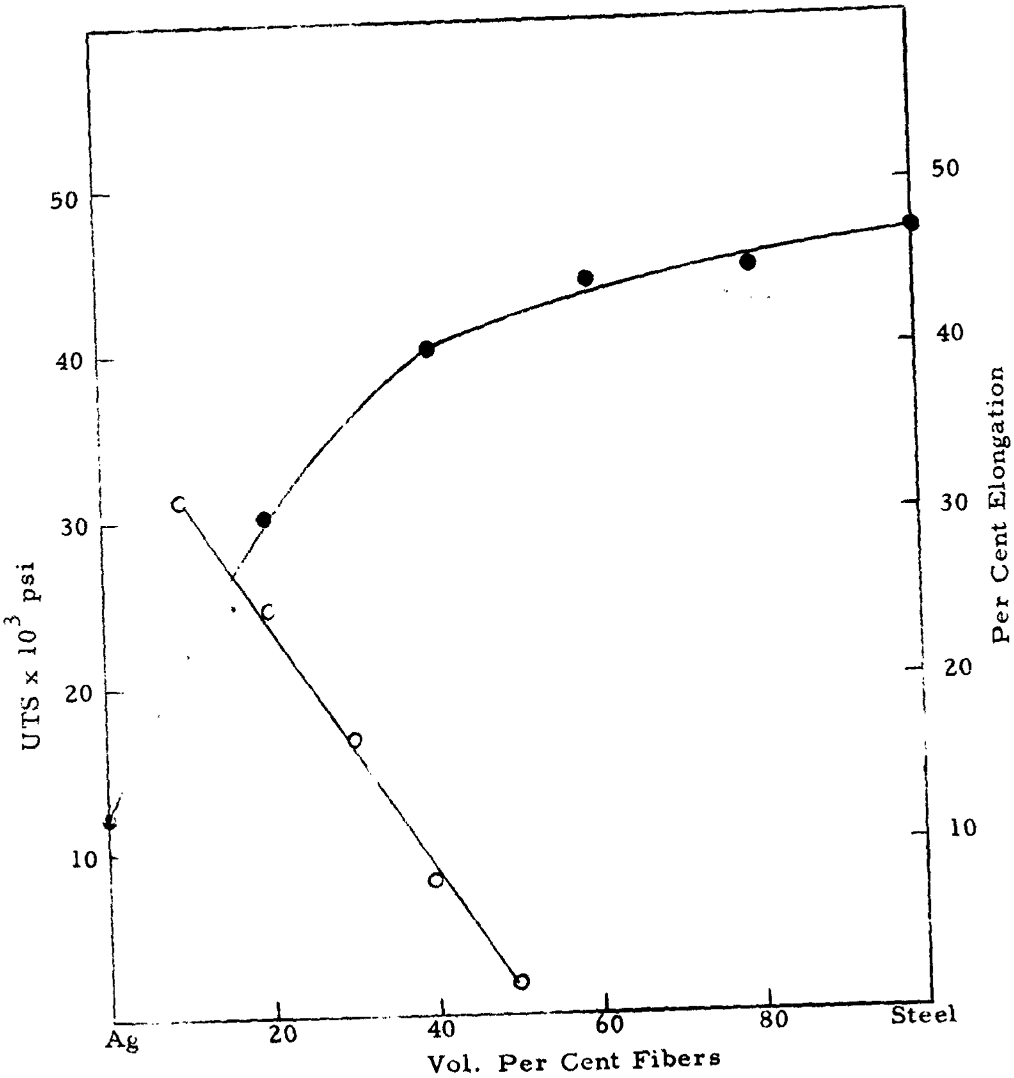
The work done on this program during the last report period confirmed the observation that the degree of alignment of short fibers in a ductile matrix has a major effect on the levels of strain obtainable in a composite. It was also noticed that with both steel-silver as well as with tungsten-silver composites containing short discontinuous aligned fibers, the strain level approaches a maximum at some 40 or 50% fiber concentration beyond which there appears to be little further increase in strain of the composite. Thus, for these systems at least, it appears that the law of mixtures is not exactly valid. Perhaps a major reason for this observation is the concurrent drop in ductility with increasing fiber concentrations.

In the last report the deformation of fracture modes of composites in these two systems were described and discussed. It is quite apparent that the maximum in strength and the concurrent minimum in ductility is accompanied by a gradual change in fracture mode from the ductile shear type of fracture in the matrix to the brittle cleavage type in the fibers. The ultimate tensile stress of these composites is reached at a strain comparable to the fracture strain in the fiber. With a metallic matrix, the strain of the composite must be discussed in terms of the elastic-plastic

model. For such composites, the stress-strain curve shows two distinct ranges--the first range is that in which both components are elastic and the second is that in which the matrix deforms plastically and the fibers elastically. In the second region the contribution of the matrix to the elastic modulus is very small because the matrix is deforming permanently. Under these conditions the load in a fiber is transferred to it via the matrix. Thus, the strength of the composites made with shorter discontinuous fiber will always be lower than those prepared with continuous filaments. The important parameters appear to be the interfiber spacing, or transfer length, and the fiber diameter.

We must keep two things in mind with regard to the deformation and fracture modes of these composites. One is that if the deformation of the composite allows for the build up of strain in the matrix alone to the level of its fracture stress, we will have what we call a pull out or fracture in the matrix. Since the ultimate fracture stress of a matrix is governed largely by the work-hardening behavior of the matrix, this behavior will be characteristic for individual metals. Secondly, it will be possible to nucleate a crack in the fiber by plastic deformation of the matrix provided the latter builds up a large strain in the fiber which may cause fracture.

Since most of the deformation and fracture work was done during the last report period, it was felt that additional experimental data would help to verify or reject the hypothesis develcped so far. One of the most widely accepted properties for design purposes is that of fracture energy. The fracture energy data, in addition to throwing some light on the toughness of the material, will also establish whether a given material could be employed for structural purposes by a design engineer. For convenience, we have plotted the data of strength and elongation of steel-reinforced silver composites in Figure 1. One can see that, confirming previous observations, the strength levels off at about 50% fiber concentrations and at the same time the ductility drops to a very small value. The notch toughness or impact data runs parallel to the ductility curve. The data in Figure 1 can only be explained with the help of the metallographic observations which indicate a gradual transition from ductile to brittle type of failure.



F[illegible] 1 - STRENGTH AND DUCTILITY OF STEEL FIBER REINFORCED SILVER COMPOSITES. SHORT, ALIGNED FIBERS, 0.002 IN. IN DIAMETER.

It is not possible to conclude from this data that higher strengths cannot be achieved in these composites. We must keep in mind that these composites were fabricated from commercially available fibers. Also, the fiber lengths and diameters were selected arbitrarily from the point of view of what could be accomplished with present-day laboratory techniques.

Most of the data collected have been analyzed in terms of the models proposed by Cox, Cottrell, and others; analytical discussions will be presented in detail in the final report. At the moment all one can say is that with proper control of the average transfer lengths for interfiber spacings, one ought to be able to allow the fiber to carry much more load prior to fracture than shown in Figure 1.

The fracture energy data for steel-reinforced silver composites are shown in Figure 2. From the points plotted in the graph, the shape of the curve is probably insignificant. What is significant, however, is that the most ductile composites possess fracture energies which are marginal from a design standpoint and that the strongest composites possess fracture energies that are one or two orders of magnitude below this level. When we look at the fracture energy data for composites containing 60 or 70% fibers, the numbers are not much greater than those obtained for glass.

This implies that considerably less homogeneous plastic work is expended in fracturing composites containing high volume fractions of the fibers of the given diameters and lengths. In the microscopic sense, and referring only to composites under discussion, as one increases the fiber concentration the transfer lengths decrease. As one decreases the fracture length in the composite, the ultimate fracture stress of the matrix will be arrived at first and, hence, the strain in the fiber will be built up to a high enough level to cause cracking.

Because fiber reinforced metals are different from dispersion hardened alloys insofar as the plastic work contribution of the matrix is concerned, it is apparent that a random degree of the transfer length will

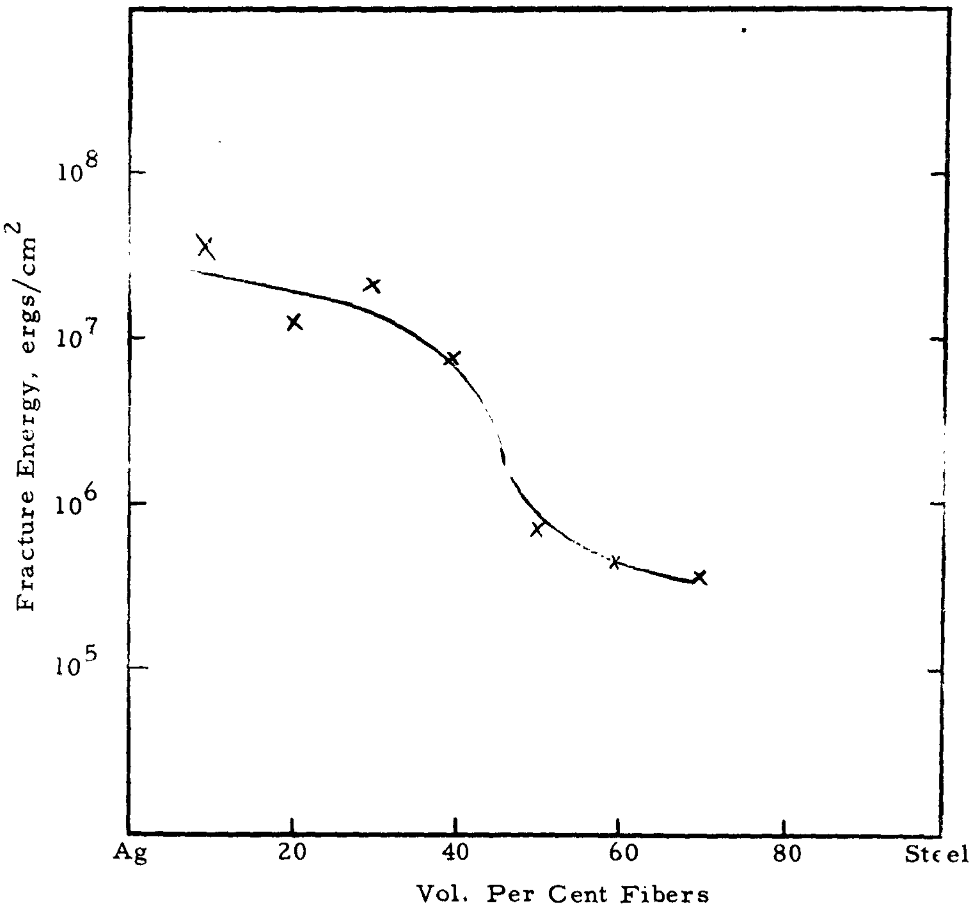


Fig. 2 - FRACTURE ENERGY FOR STEEL FIBER REINFORCED SILVER, SHORT, ALIGNED FIBERS, 0.002 IN. IN DIAMETER.

only defeat our purpose of transferring maximum load to the fiber at minimum strain in the matrix. It may be generally stated, therefore, that for a given diameter of the fibers the critical transfer lengths are fixed and cannot be varied at will. With a decrease in fiber diameter, one can increase the transfer length or interfiber spacing and thereby obtain a greater degree of strengthening.

Figure 3 shows microstrain measurements of tungsten-reinforced silver wherein the tungsten fibers were short, discontinuous, and mostly aligned in the direction of plotted stress. These composites were prepared for simultaneous microstrain and metallographic work; Figure 3 of the last report (IITRI-B6020-4) shows that the fabrication technique left the structure of the tungsten fibers unchanged. The data in Figure 3 relate to the microstrain behavior of tungsten-silver composites and shows that the field strength at extremely small strains is independent of fiber concentration. This means that the stress necessary to initiate dislocation motion in silver is the same in pure metal as well as in the matrix in the composite. As the deformation progresses, however, the fibers act as obstacles to slip, and dislocations pile up at the interface. With increasing concentrations of tungsten fibers the available slip length decreases and a larger number of dislocations pile up at the interface for a given strain.

This phenomenon results in a greater rate of work hardening because it takes a larger stress to force new dislocations in the pile up. This analysis is quite similar to the Petch analysis on the strengthening efforts of grain boundaries. Lastly, one can see from the graphs in Figure 3 that as one increases the fiber concentration beyond about 40%, the rate of work hardening changes measurably and fracture occurs at stresses somewhat below the engineering yield point.

The work on continuously aligned fiber reinforced silver is in progress at the moment and particular care has to be taken to see that none of the fibers are fractured soon after fabrication. Electron-microscopic studies of the fracture surfaces of these composites have not been too successful to date because of the problems associated with the replication techniques.

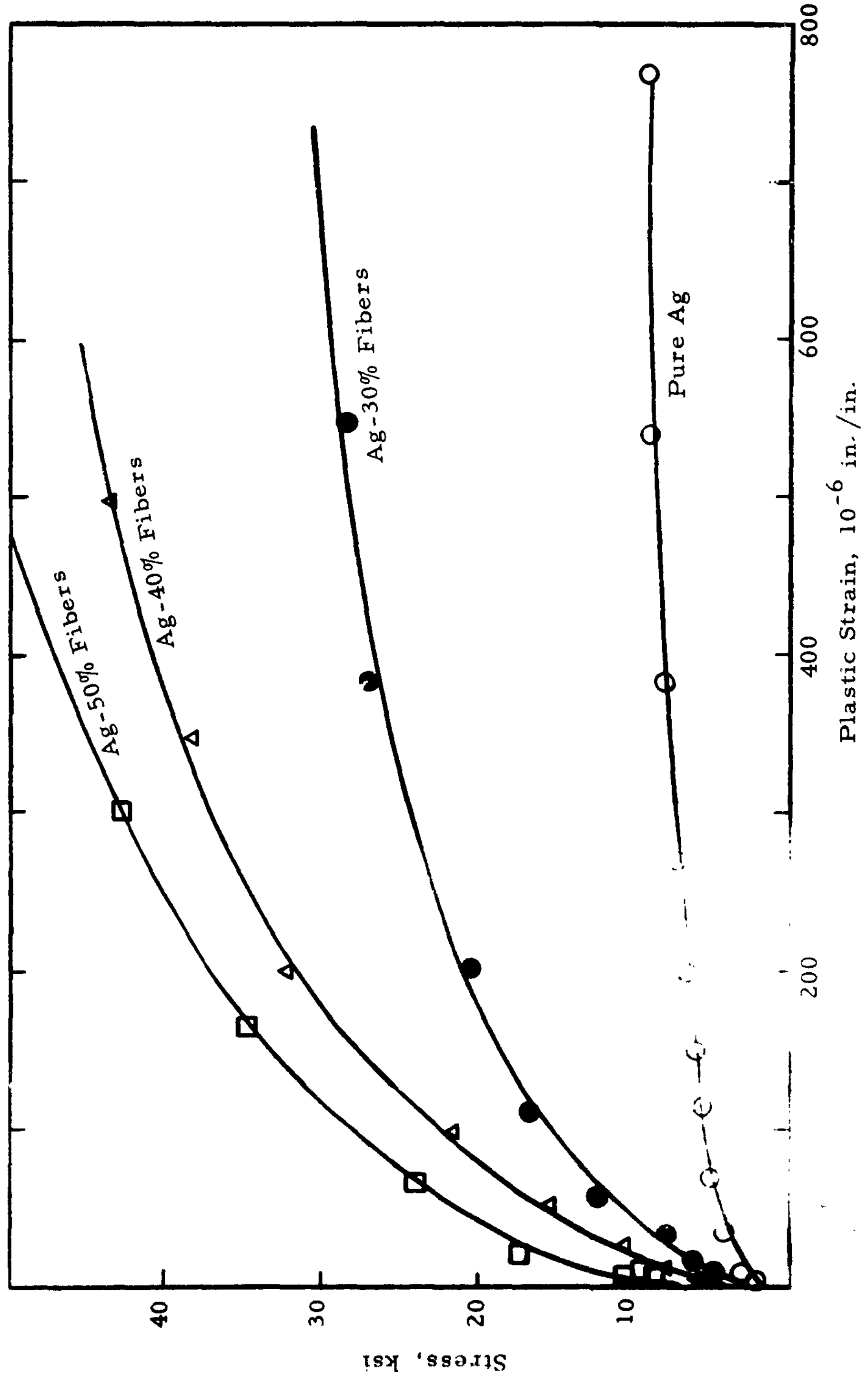


Fig. 3 - STRESS-PLASTIC STRAIN CURVES FOR PURE Ag AND W-Ag COMPOSITES OF VARIOUS FIBER CONCENTRATIONS.

IV. CONCLUSIONS

The current investigations indicate that with short discontinuous aligned fibers in a composite, only a fraction of the fiber strength is realized. The ductile-to-brittle transition found in steel-silver composites was also found in tungsten-silver composites. The fracture energy measurements were most helpful in clarifying this ductile-to-brittle behavior and the analysis of the fracture modes.

V. FUTURE WORK

Deformation and fracture mechanisms in composites made with continuous filaments are in progress. This work, combined with the microstrain measurements, should throw some further light on the behavior of such composites. The fracture energy work will be extended to all the composites mentioned to date and prepared with short fibers or continuous filaments.

VI. LOGBOOKS AND CONTRIBUTING PERSONNEL

The data recorded herein are recorded in IITRI Logbook No. C-14233. N. M. Parikh and Robert Adamski contributed to this program.

Respectfully submitted,
IIT RESEARCH INSTITUTE

N. M. Parikh

N. M. Parikh
Assistant Director
Metals and Ceramics Research

Tech Rev - DJM

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